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TESTING OF A 40 KW PHOSPHORIC ACID FUEL CELL POWER PLANT AT B.C. HYDRO

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BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

RESEARCH AND DEVELOPMENT

40 kW PAFC POWER PLANT TEST PROJECT

AT

B.C. HYDRO

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SUMMARY

With the support of the National Research Council Canada (NRC) and Energy, Mines and Resources Canada, (EMR) B.C. Hydro installed an on-site 40 kW phosphoric acid fuel cell (PAFC) power plant. The installation constitutes a mobile fuel cell power system demonstration unit complete with controls and monitoring equipment. B.C. Hydro and Ontario Hydro agreed to jointly support the Fuel Cell Test Project.

The overall objective of the test project was to demonstrate the performance and operating characteristics of the PAFC power plant and to establish the potential for implementation of fuel cell energy systems as a new option for Canadian Utilities.

B.C. Hydro has trained designated personnel responsible for the management, technical supervision, operation and maintenance of the fuel cell power plant.

The selected site was prepared and the power plant was installed in a custom designed road mobile trailer together with instrumentation, a data acquisition system and minicomputer for on-site data analysis.

The commissioning and start-up of the power plant was successfully completed.

Following the start-up, the power plant was put in the normal operating mode, producing utility-grade electricity and thermal energy for the B.C. Hydro R&D Centre.

Successful operation and testing of the 40 kW PAFC power plant was conducted at the B.C. Hydro R&D Centre, Surrey, B.C. from 7 November

1985 to 1 May 1987 in both grid-isolated and grid-connected modes of operation (as of 5 May 1987 the power plant was still operating in grid-connected mode).

The power plant was maintained and operated in grid-isolated mode of operation for cumulative 5253.6 hours, and in grid-connected mode of operation for cumulative 2688.0 hours (to 1 May 1987).

The longest continuous run in grid-isolated operating mode was 2205.6 hours which was the longest continuous operation recorded with this type of fuel cell power plant. The longest continuous operation in grid-connected operating mode was 1271.1 hours. The availability of the power plant was 68 percent in grid-isolated operation, and 74 percent in grid-connected operation.

The average grid-isolated electrical generation efficiency, based on Lower Heating Value of natural gas of 34,600 kJ/m^{3}n, was 28.9 percent with the best 30 minutes performance of 39.3 percent. The average grid-isolated thermal recovery efficiency was 15.0 percent with the best 30 minutes recovery of 39.0 percent.

The average grid-connected electrical generation efficiency was 39.4 percent with the best 30 minutes performance at 40.8 percent. The average grid-connected thermal recovery efficiency was 21.1 percent with the best 30 minutes recovery of 39.3 percent.

There were no failures of the unique components: the fuel cell stack or fuel processor. The failures that occurred were primarily with mechanical and electronic logic components.

This test project was complementary to the 40 kW On-Site Fuel Cell Field Test Program sponsored by the US Gas Research Institute (GRI) and the US Department of Energy (DOE) in which 46 field test fuel cell power plants and three pre-field test units were manufactured and field tested for a total of over 300,000 hours.

Résumé

Avec l'appui du Conseil national de recherches Canada (CNRC) et du ministère de l'Énergie, des Mines et des Ressources (EMR), la société B.C. Hydro a installé une pile à combustible à l'acide phosphorique (PCAP) d'une capacité de 40 kilowatts (kW). L'unité mobile de démonstration est en soit un système générateur d'électricité doté d'équipements de contrôle et de surveillance. B.C. Hydro et Hydro-Ontario soutiennent également le projet.

L'objectif premier du projet est de démontrer le rendement et les caractéristiques d'exploitation du générateur PCAP et d'évaluer le potentiel des piles à combustible comme nouvelle source d'énergie pour les services publiques du pays.

En tout état de cause, B.C. Hydro compte dans ses rangs du personnel compétent chargé de la gestion, de la surveillance technique, de l'exploitation et de l'entretien de cette installation.

Après l'aménagement du site, la pile fut installée dans une remorque conçue à cette fin et équipée d'instruments, d'un système de saisie des données et d'un micro-ordinateur pour en effectuer le traitement sur place.

La mise en service et la période de démarrage furent sans encombre.

Une fois la période de démarrage terminée, la "centrale" fut exploitée à régime normal et alimenta le centre de recherche et de développement de B.C. Hydro en électricité et en énergie thermique de qualité commerciale.

Couronnés de succès, les essais et l'exploitation du générateur PCAP de 40 kW furent effectués au centre de recherche et de développement de B.C. Hydro, à Surrey (Colombie-Britannique), entre le 7 novembre 1985 et le 1er mai 1987. On étudia alors son fonctionnement en circuit autonome et en circuit intégré, c'est-à-dire, couplé au réseau (au 5 mai 1987, la pile à combustible était encore branchée au réseau).

Elle fonctionna, en circuit autonome, pour une durée totale de 5 253,6 heures et, en circuit intégré, pour 2 688 heures (au 1er mai 1987).

En circuit autonome la plus longue période d'exploitation continue enregistrée fut de 2 205,6 heures, un record pour ce genre de pile à combustible. En circuit intégré, elle fut de 1 271,1 heures. Pour ce qui est du taux de disponibilité des deux modes, il est de 68 pour 100 (en autonome) et de 74 pour 100 (en intégré).

En moyenne, le rendement en circuit autonome, fondé sur le pouvoir calorifique minimal du gaz naturel de 34 600 kJ/m^{3}n, a été de 28,9 pour 100, avec une pointe de 39,3 pour 100 pour une période étalon de trente minutes. En circuit intégré, le taux moyen de conversion thermique est de 15 pour cent, avec une pointe de 39 pour 100 pour une période étalon de trente minutes.

En circuit intégré, le taux de charge moyen était de 39,4 pour 100, le maximum enregistré étant de 40,8 pour 100 pour une période étalon de trente minutes. Le taux moyen de conversion thermique était de 21,1 pour 100, avec un rendement maximal de 39,3 pour 100 enregistré au cours d'une période étalon de trente minutes.

Les composantes principales n'ont connu aucune défaillance : ni l'unité de traitement du combustible ni la série de cellules électrolytiques. Les pannes survenues sont principalement attribuables à des pièces mécaniques ou au système de traitement des données.

Ce projet d'essai complète le programme américain (40 kW On-site Fuel Cell Field Test Program) qui, parrainé par l'US Gas Research Institute (GRI) et l'US Department of Energy (DOE), a permis de construire 46 piles à combustible pour des essais sur le terrain et trois unités pour des essais préliminaires et de compiler les résultats de plus de 300 000 heures de test.

1.0 - INTRODUCTION

Fuel cell power plants provide a new option for generating electrical and thermal energy to meet utility needs and are expected to enter commercial utility application in the next decade.

Before this new equipment can be introduced into a utility system, appropriate technical information, performance data and operating experience are required to determine the effect on a utility system operation and to develop an acceptable level of confidence. Thus an operational feasibility project was undertaken to establish the acceptance of and commitment to fuel cell energy systems for Canadian utilities.

With the support of the National Research Council Canada (NRC) and Energy, Mines and Resources Canada (EMR), B.C. Hydro installed an on-site 40 kW phosphoric acid fuel cell (PAFC) power plant at it's Research and Development Centre in Surrey, B.C. The installation constitutes a mobile fuel cell power system demonstration unit complete with controls and monitoring equipment.

B.C. Hydro and Ontario Hydro agreed to jointly support the Fuel Cell Test Project. The project provided a unique opportunity for participating utilities to share in the operation and testing of a fuel cell power plant. The experience gained in installing and operating this natural gas-fuelled unit will be invaluable in specifying the general performance requirements for Canadian utilities and in the development of a fuel cell generation program for Canada.

The overall objective of the on-site 40 kW PAFC power plant test project was to demonstrate the performance and operating characteristics of the power plant and to establish the potential for implementation of fuel cell energy systems as a new option for

Canadian utilities. To reach this objective, it was desirable that the following goals be met:

1. Install, maintain and operate the power plant.

2. Establish operational feasibility and availability of the power plant.

3. Verify the fuel consumption and output characteristics.

4. Verify the environmental characteristics.

5. Verify the practicality and overall viability of the system.

6. Document the operation and maintenance.

7. Assess the economic performance.

8. Identify problems and necessary improvements.

9. Establish scenarios for commercial service.

10. Inform the public.

Successful operation and testing of the 40 kW PAFC power plant was conducted during the period from 7 November 1985 to 1 May 1987 (as of 5 May 1987 the power plant was still operating).

The project provided appropriate technical information, performance data and operating characteristics of the 40 kW PAFC power plant.

This activity was complementory to the 40 kW On-Site Fuel Cell Field Test Program sponsored by the US Gas Research Institute (GRI) and the US Department of Energy (DOE) in which 46 field test fuel cell power

plants and three pre-field test units were manufactured and field tested for a total of over 300,000 hours.

In the following, the activities described comprise the scope of work of the Fuel Cell Power Plant Test Project undertaken by B.C. Hydro and Ontario Hydro.

2.0 - PERSONNEL TRAINING

B.C. Hydro designated personnel responsible for the project activities. The personnel included a Project Manager responsible for all activities and functions on the project, a Project Engineer responsible for technical operations and data collection, instrumentation and operating personnel responsible for operation and maintenance, and specialists providing necessary support to the project. Three individuals involved in the fuel cell power plant installation and test activities were trained by the International Fuel Cells (IFC) to familiarize them with principles, installation, operation, performance and maintenance of the fuel cell power plant.

A two week training course covered the following material:

- Power plant description
- Power plant performance
- Instrumentation
- Shipping
- Handling
- Plumbing hookup
- Electrical hookup
- Power plant operation
  - Start, run, shutdown
  - Data analysis
- Maintenance
  - Scheduled
  - Automatic shutdowns
  - Repair

Training was successful as shown by the subsequent ability of the personnel to install and maintain the power plant.

3.0 - SITE SELECTION, DESIGN AND PREPARATION

The selected site for the fuel cell power plant was located adjacent to the B.C. Hydro R&D Centre in Surrey, B.C. (Figure 1). The site was suitable for all program objectives including technical, operational, environmental, institutional, regulatory, market and business assessment.

Thermal and electrical load data for the site over a 1-year period were obtained. The site was instrumented and the necessary services from the B.C. Hydro R&D Centre provided. These included electrical and mechanical interfaces. The site also had a thermal storage system.

The fuel cell power plant operated grid-isolated from 7 November 1985 to 24 September 1986 providing electricity for the lighting of the main floor of the R&D Centre and domestic hot water heating for the Centre. The fuel cell power plant output was controlled solely by the electrical demand of the building.

During October 1986 the power plant was shut down to allow the installation of the grid-connect unit (GCU).

From 3 November 1986 to 1 May 1987 the fuel cell power plant operated grid-connected. The site had a grid-independent load (main floor lighting) which was automatically connected in the event of the loss of the grid. The electric output of the grid-connected plant was controlled by the dispatched power set point at 37 kW and the fuel cell operation was unaffected by the electrical demand of the building. Fuel cell heat was used for domestic hot water heating.

4.0 - INSTALLATION OF THE POWER PLANT

The power plant was installed in accordance with the Installation Manual provided by IFC. The 40 kW PAFC power plant weights 5000 kg and its volume is approximately 10 m^3. The exterior dimensions of the power plant are 3.21 m x 1.63 m x 1.98 m (126.5 in x 64 in x 78 in). The grid-connect unit weighs 680 kg and occupies the volume of approximately 1.5 m^3. The overall dimensions of the GCU are 1.42 m x 0.79 m x 1.30 m (56 in x 31 in x 51 in).

Transportation and handling of the power plant was carried cut by air-ride cab and trailer and fork lift truck respectively.

Upon receipt from the carrier the power plant was inspected for damage and shock exerted during transportation (impact indicators). The power plant was then reconfigured from the shipping state to the operational state.

The power plant was installed in a custom designed 13.7 m x 3.0 m (45 ft x 10 ft) road mobile trailer together with a data acquisition system and minicomputer for on-site data analysis, to be a totally self-contained fuel cell demonstration unit (Figure 2).

All electrical and mechanical interfaces to the site energy system were completed. The electrical interfaces included output power, start power, instrumentation, diagnostic interface and earth ground connections. The mechanical interfaces included fuel gas, heat recovery, water overflow, nitrogen and diagnostic fluid interfaces.

Instrumentation and ancillary equipment were supplied. These included:

1. Transfer switch to transfer the building load automatically from the fuel cell power plant to back-up power in the event of a shutdown (grid-isolated unit).

2. Circulation pumps and piping to connect the fuel cell power plant to the thermal recovery equipment at the B.C. Hydro R&D Centre.

3. Sensing and recording equipment to measure power plant performance, electrical and thermal load parameters and environmental conditions.

4. Warning and alarm system.

5. Electric protection for grid-connected operation.

The construction and delivery of the trailer took 123 days (21 December 1984 - 22 April 1985). Further finishing work on the trailer was required before it was possible to complete the power plant installation. Once the trailer was completed the power plant was installed in 130 days (7 June 1985 - 15 October 1985).

Data Acquisition System was specified, designed and installed by Science Applications Inc.

5.0 - COMMISSIONING AND START-UP

Inspection was made to assure that the power plant had been installed and connected to the site in accordance with the information contained in the Installation Manual provided by IFC.

As part of the commissioning, the power plant was retrofitted to the latest standards and several modifications and repairs to the power plant were made. Detailed description of the power plant modifications is given in Appendix A.

Prestart preparation of the power plant was carried out according to the instructions contained in the Operating Manual issued by IFC.

The following power plant systems and functions were inspected, calibrated and prepared for normal operation.

1. power system
2. air processing system
3. fuel processing system
4. thermal management system
5. water treatment system
6. inverter
7. start-up power supply
8. control system
9. internal electrical system
10. ac power phasing
11. coolant loop
12. water demineralizer
13. heat exchangers
14. electrical sensors
15. data acquisition system

16. transfer switch
17. gas meter and electrical meters
18. nitrogen purge system
19. safety equipment

Start-up was carried out in accordance with the procedures described in the Operating Manual issued by IFC. Start-up was automatic following manual initiation and required approximately five hours when started from 20°C ambient conditions. The commissioning and the first start-up was done under the supervision of an IFC field engineer.

The power plant was controlled by a programmed microcomputer which provided the control intelligence for the four basic power plant operating modes: start, run, shut-down and water conditioning.

The power plant responded automatically to the load demand by sensing the power being delivered and metered the fuel flow as required.

The control system monitored various internal operating signals and automatically shut the power plant down if any out-of-limits condition occurred. The power plant could be shut-down manually at the discretion of the operator. After shut-down the power plant was cooled down before restarting.

The first start-up of the fuel cell power plant occurred on 7 November 1985. The power plant operated for 2.5 hours at between 0 and 24 kW electrical load when it was automatically shut down because of the loss of cooling water.

6.0 - OPERATION AND MAINTENANCE

Following the start-up, the power plant was put in the normal operating mode, producing utility-grade electricity and recoverable thermal energy. The power plant operated automatically and provided output power as a function of the site electrical load demand, (in grid-isolated mode of operation) or as a function of dispatched power set point (in grid-connected mode of operation). The power plant operating systems were checked and performance confirmed prior to unattended power plant operation. These included:

1. Run Parameters. The power plant run parameters were recorded and correlated with the operating curves.

2. Feedwater System. The operation of the feed and boost pump together with the feedwater pressure was monitored.

3. Water Tank. Water recovery is a strong function of ambient temperature and load. The water tank level was observed and maintained so that no water deficit resulted. During testing, deionized water make-up was used instead of recirculating condensate water.

4. Coolant System. The water quality of the coolant system was checked daily until desired conditions were achieved. Turbidity, conductivity and oxygen measurements were made and recorded. Operating pressures, temperatures and flows were continuously monitored.

Scheduled maintenance as a function of the operating time was performed in accordance with the Maintenance Manual provided by IFC. Repair maintenance for operational problems and automatic shutdown

parameters was provided. Retrofits and modifications to the power plant were carried out as required in cooperation with IFC.

Successful operation and testing of the 40 kW PAFC power plant was carried out at the B.C. Hydro R&D Centre, Surrey, B.C. from 7 November 1985 to 1 May 1987 in both grid-isolated and grid-connected mode of operation.

The air temperature in the fuel cell trailer varied from a low mean value of 20°C to a high 35°C during the testing period.

6.1 Grid-Isolated Mode of Operation

The operation and testing of the power plant in the grid-isolated operating mode was conducted at the R&D Centre from 7 November 1985 to 24 September 1986. During that time a total of 5253.6 operating hours were accumulated. The longest continuous run was 2205.6 hours, the longest continuous operation recorded with this type of fuel cell power plant. The availability of the power plant during this period was 68 percent which compares well with the cumulative availability of 46 power plants employed in the GRI/DOE program of 63 percent. (The total fleet operating time in the GRI/DOE program was over 300,000 hours with one plant having accumulated over 11,000 operating hours and the longest continuous run recorded being 2165 hours.)

There were no failures of the unique components: the fuel cell stack or fuel processor. The failures that occurred were primarily with mechanical and electronic logic components.

Table 1 summarizes the operation and performance of the fuel cell power plant during 7 November 1985 - 24 September 1986 in the grid-isolated mode of operation.

Ten automatic shut-downs occurred during the grid-isolated operation because of the loss of the coolant water flow.

The time loss caused by forced outages ranged between 1 and 816 hours. The longest time out of operation being 816 hours. The long shutdown periods were caused mainly by weekends, holidays, vacations and modifications to the water treatment system.

The total natural gas consumption during grid-isolated operation of the power plant was 372,448 kWh (based on Low Heating Value of 34,600 kJ/m^{3}n). The total generated electricity was 108,318 kWh. The total heat recovered from the power plant heat exchangers was not measured due to problems with the data acquisition system.

The average grid-isolated electrical generation efficiency based on Low Heating Value of natural gas of 34,600 kJ/m^{3}n, was 29.1 percent with the best 30 minutes performance of 39.3 percent.

The average grid-isolated thermal recovery efficiency was 12.4 percent with the best 30 minutes recovery of 39.0 percent. The low thermal recovery was mainly due to the low thermal requirements of the building and to the fouling of heat exchangers.

The best recorded grid-isolated coincident 30 minutes electrical generation and thermal recovery efficiency was 36.6 percent and 30.3 percent respectively i.e. the overall energy efficiency of 66.9 percent was achieved.

During grid-isolated operation the power plant operated at an average electric capacity factor of about 50 percent and a thermal capacity factor of about 20 percent. About 41.5 percent of all input fuel was converted to useful energy.

The trailer service demand had an average load of about 5 kW with peak 30 minutes demands as high as 31 kW. High demands were experienced during the power plant start-ups on cold winter days.

The electrical generation efficiency versus power levels taken over an extended time period is shown in Figure 3 together with the IFC electrical efficiency specification. The measured power plant electrical efficiency was at or slightly below the IFC specification during the testing period. The lower efficiency was mainly due to the excessive start sustain heater operation.

Figure 4 presents both electrical and overall power plant efficiency over its operating period. The lower than expected overall efficiency was mainly due to the low thermal recovery.

Measured thermal outputs of the power plant averaged below the IFC specification for the low-grade heat exchanger. Figure 5 illustrates this finding for an extended time period of operation. The low thermal outputs of the power plant were due to the low thermal requirements of the building.

High-grade heat recovery is shown in Figure 6. As with 40 kW power plants field tested in the USA, the high-grade heat exchanger measured outputs were consistently below IFC specification. In part of the program the high-grade heat exchanger was by-passed on the customer side so that no heat was recovered from this source. This was necessary to avoid operational problems and automatic shut-downs caused by the high-grade heat exchanger fouling.

6.2 Grid-Connected Mode of Operation

During October 1986 the power plant was shut down to allow the installation of the grid-connect unit (GCU), which was completed 27 October and the unit was recommissioned 28-31 October 1986. The

operation and testing of the power plant in the grid-connected mode, which synchronizes the electrical output of the fuel cell with the B.C. Hydro electric system, was conducted at the R&D centre from 3 November 1986 to 1 May 1987. During that time a total of 2688.0 operating hours were accumulated. The longest continuous run was 1271.1 hrs. The availability of the power plant during this period was 74 percent which compares well with the cumulative availability of 46 power plants employed in the GRI/DOE program of 63 percent.

There were no failures of the unique components: the fuel cell stack or fuel processor. The only failures that occurred were with mechanical pumps, gaskets and valves.

Table 1 summarizes the operation and performance of the fuel cell power plant during 3 November 1986 - 1 May 1987 in the grid- connected mode of operation (as of 5 May 1987 the power plant was still operating in grid-connected mode).

Six automatic shut-downs occurred during the grid-connected operation because of loss of the coolant water flow and failure of the air and fuel control valves.

The time loss caused by forced outages ranged between 12 and 720 hours. The longest time out of operation being 720 hours. The long shutdown periods were caused mainly by weekends, holidays and vacations.

The total natural gas consumption during grid-connected operation of the power plant was 257,834 kWh (based on Low Heating Value of 34,600 kJ/m^{3}n). The total generated electricity was 101,658 kWh. The total heat recovered from the power plant heat exhangers was not measured due to problems with the data acquisition system.

The average grid-connected electrical generation efficiency, based on Low Heating Value of natural gas of 34,600 kJ/m³n was 39.4 percent with the best 30 minutes performance of 40.8 percent.

The average grid-connected thermal recovery efficiency was 21.1 percent with the best 30 minutes recovery of 39.3 percent.

The best recorded grid-connected coincident 30 minutes electrical generation and thermal recovery efficiency was 39.4 percent and 38.5 percent respectively, i.e. the overall energy efficiency of 77.9 percent was achieved.

During grid-connected operation the power plant operated at an average electric capacity factor of about 94 percent and a thermal capacity factor of about 51 percent. About 60.5 percent of all input fuel was converted to useful energy.

The trailer service demand had an average of about 7 kW with peak 30 minutes demands as high as 38 kW. High demands were experienced during the power plant start-ups on cold winter days.

The electrical generation efficiency versus power levels taken over an extended time period is shown in Figure 3 together with the IFC electrical efficiency specification. The measured power plant electrical efficiency was at or slightly below the IFC specification during the testing period. The lower efficiency was mainly due to the excessive start sustain heater operation.

Figure 4 presents both electrical and overall power plant efficiency over its operating period. The lower than expected overall efficiency was mainly due to the low thermal recovery.

Measured thermal outputs of the power plant averaged below the IFC specification for the low-grade heat exchanger. Figure 5 illustrates this finding for an extended time period of operation. The low

thermal outputs of the power plant were due to the low thermal requirements of the building.

High-grade heat recovery is shown in Figure 6. As with 40 kW power plants field tested in the USA, the high-grade heat exchanger measured outputs were consistently below the IFC specification. In part of the program the high-grade heat exchanger was bypassed on the customer side so that no heat was recovered from this source. This was necessary to avoid operational problems and automatic shut-downs caused by the high-grade heat exchanger fouling.

In the GRI/DOE fuel cell testing program the measured power plant electrical generation efficiency was on average 100 percent of the predicted value and low-grade heat utilization was on average 90 percent of the predicted value.

Performance of the fuel cell stack after 6200 hours operation is shown in Figure 7 and is compared to design projections. As can be seen, no deterioration of stack performance after 6200 hours operation was observed.

Figure 8 plots net ac power plant output vs dc fuel cell stack output over the operating range of the power plant. The areas between the curves represent the power required for stack heating, inverter losses and auxiliary loads for mechanical drives. This explains the lower electrical efficiency of the power plant at low loads (<20 kW).

7.0 - TESTING PROGRAM

Testing of the power plant was carried out to establish and confirm it's performance. The following tests were performed:

1. No Load Electrical Characteristics.

With fuel cell system operating at no net ac load (i.e. B1 breaker open), the following measurements were made:

- three phase ac voltage (Ø to Ø, Ø to N)
- dc stack voltage (with DAS)

The results are shown in Table 2 for both grid-isolated and grid-connected operation. Under no net output power (kW = 0) the phase-to-neutral voltages were 126 V and the dc stack voltage was 212 V in agreement with the manufacturers specification (<220 V).

2. Zero to Full Load Electrical Characteristics.

A variable electrical load (B1 breaker closed) was used over the range of 0 kW to 40 kW in discrete steps to allow the following measurements to be made.

- three phase ac voltage (Ø to Ø, Ø to N).
- line currents
- three phase power
- dc stack voltage (with DAS)

The results are shown in Table 2 for both grid-isolated and grid-connected operation. The phase-to-neutral voltages were about 122 V for grid-isolated operation and 111 V for grid-connected operation and phase currents varied between 47 A and 122 A in

agreement with the required operating characteristics of the system. The dc stack voltage was maintained below 220 V by internal load management.

3. Inverter Operating Characteristics.

The inverter was tested in grid-isolated and grid-connected operating mode. The following characteristics were assessed:

- harmonic distortion of both the voltage and the current
- Volt-Ampere-Reactive (VAR) power

The percent total harmonic distortion was calculated based on the following formula:

$$\%THD = \sqrt{\frac{\text{(sum of squares of amplitudes) of all harmonics}}{\text{(square of amplitude of fundamental)}}} \times 100\%$$

The results of 36 harmonic distortion measurements are summarized in Table 2. The harmonic distortion of the output voltages was within manufacturers specification for grid-isolated operation (<8%) and exceeded manufacturers specification for grid-connected operation (<4%). The individual harmonics were approximately constant at various power levels resulting in higher relative harmonic content at low power levels.

4. Load Following Characteristics

The response of the fuel cell power plant to changing load was recorded in both grid-isolated and grid-connected operating mode. The

results are shown in Figure 9. The specified full up or down transient response is within two cycles (32 ms).

5. Low-Grade Thermal Recovery

The following measurements were made over a range of fuel cell operating loads 10 kW to 40 kW:

- temperature limits
- heat exchanger performance
- input/output temperature
- flowrate
- thermal output
- thermal load following

The performance of the low-grade heat recovery system was discussed earlier in Section 6.

6. High-Grade Thermal Recovery

The following measurements were made over a range of fuel cell operating loads from 10 kW to 40 kW:

- temperature limits
- heat exchanger performance
- input/output temperature
- flowrate
- thermal output
- thermal load following

The performance of the high-grade heat recovery system was discussed earlier in Section 6.

7. Environmental Characteristics

The following measurements were made:

- atmospheric emissions
- water quality
- audio noise

Atmospheric emissions were as follows:

NO_x	ND
SO_2	ND
CO	0.14×10^{-6} kg/GJ
CO_2	67×10^{-6} kg/GJ
Particulate	ND

Water effluent was about 0.5 L/min (85×10^{-6} L/GJ heat input). It's analysis was as follows:

pH	5.2	
alkalinity (as $CaCO_3$)	<5	mg/L
total dissolved solids	8	mg/L
total suspended solids	<5	mg/L
chloride (Cl)	<0.1	mg/L
flouride (F)	0.2	mg/L
nitrate (NO_3)	0.04	mg/L
phosphate (PO_4)	3.2	mg/L
sulphate (SO_4)	2.6	mg/L

aluminum	0.086	mg/L
boron	0.005	mg/L
calcium	0.2	mg/L
chromium	0.003	mg/L
cobalt	0.001	mg/L
copper	1.3	mg/L
iron	0.5	mg/L
lead	0.032	mg/L
magnesium	0.02	mg/L
manganese	0.043	mg/L
nickel	0.3	mg/L
potassium	<0.05	mg/L
silicon	0.042	mg/L
silver	<0.001	mg/L
tin	<0.02	mg/L
titanium	<0.001	mg/L
vanadium	<0.002	mg/L
zinc	<0.01	mg/L

These results demonstrate the cleanliness of the fuel cell power plant operation.

Power plant noise measurements indicate that the specification figure of 60 dBA at 4.6 m (15 ft) was met.

The power plant operation and performance in both grid-isolated, and grid-connected mode of operation compared well with the design projections. Almost all of the specification items listed below were met:

- Start-up
  - 5.5 hours
  - Semi-automatic
- Fuel Pressure
  - 100 mm (4") H_2O gas pressure
- Operation on load
  - Automatic
  - Power Range
    - 0 - 40 kW
  - Fuels
    - Pipeline natural gas
  - Electrical Efficiency (LHV)
    - 39% at 20 to 40 kW (500 hrs)

- Water Recovery
  - Water recovery system was modified so that water condensate was discarded (see Appendix A, Item 3)

- Electrical Characteristics
  - Voltage regulation - ±5%
  - Transient voltage recovery - 2 cycles
  - Fault clearing - 300 amps line-to-line at zero volts for 5 seconds
  - Frequency stability - ±.0002% per year (grid-isolated)
  - Total harmonic distortion <8% (grid-isolated)
  - Total harmonic distortion <4% (grid-connected)
  - Electromagnetic characteristics - will not degrade electrical devices at 3 m (10 ft)
  - Power factor - 0.85 (40 kW/47 kVA)
- Noise at 4.6 m (15 ft) - 60 dBA
- Emissions - kg per GJ/pounds per million Btu heat input

NO_x	0.009/0.02
SO_2	0.00001/0.00003
Particulate	0.000001/0.000003
Smoke	None
THC	0.009/0.02

- High-grade heat - 59,000 kJ/hr (56,000 Btu/hr) at 43°C (110°F) ambient, at rated power (35,000 kJ/hr achieved).
- Low-grade heat - 105,000 kJ/hr (100,000 Btu/hr) at -32°C (-25°F) ambient, at rated power
- Shutdown - manual and automatic for safety
- Operation
  - Grid-Connected - Connected through Grid-Connect Unit (GCU)
  - Grid-Isolated - Connected directly to electrical load

8.0 - DATA COLLECTION, EVALUATION AND REPORTING

The approved Data Acquisition System (DAS) installed at the test site was used as a measuring device where applicable. For measurement of parameters not monitored by the DAS, portable test equipment was used.

A Data Logbook was maintained in order to document the day-to-day operation and maintenance of the fuel cell power plant.

The Logbook consisted of data sheets necessary to record all power plant test activities. These included: Start-up Data Sheet, Operating Data Sheet, Cell Voltage Data Sheet and General Comment Data Sheet. All sheets were numbered as used. All completed sheets were kept in chronological order by date and time.

The reported information was used to evaluate reliability, availability and maintenance of the powerplant.

Monthly reports were prepared which included all pertinent information of equipment performance, thermal and electrical load data, accumulated operating time, outages and downtime.

At the completion of the test program the results of testing were summarized, evaluated, and presented. Assessment is included in the report.

Table 1

Fuel Cell Power Plant Operating Data

Start No.	Date 1985 - 1987	Duration hr	Fuel Consumption kWh[1]	Net kWh	Electricity Output Range kW	Ave. kW	30minHi kW	Peak Hi kW	Capacity Factor[2]	Eff. %	Heat Exch. kWh[3]	Heat Output Ave. kW	30minHi kW	Capacity Factor[2]	Eff. %
					GRID-ISOLATED OPERATION										
1	Nov 07	2.5	155	48	0-32	19.2	32.0	-	.48	31.0	(4)	-	-	-	-
2	Nov 12	517.1	38,623	11,203	7-43	21.6	43.3	43.3	.54	29.0	1,925	3.7	18.2	.10	5.0
3	Dec 05	0.6	62	10	0-20	16.7	22.6	40.0	.42	16.1	(4)	-	-	-	-
4	Dec 11	0.5	99	12	0-20	24.0	-	-	.60	12.1	(4)	-	-	-	-
5	Jan 08	2,205.6	176,617	50,777	2-43	23.0	40.8	43.0	.56	28.8	24,615	11.2	35.6	.28	13.9
6	Apr 11	335.7	22,229	6,773	2-40	20.2	38.0	-	.50	30.5	(4)	-	-	-	-
7	May 08	19.0	1,541	428	2-40	22.5	38.0	-	.56	27.8	(4)	-	-	-	-
8	May 09	1,403.2	85,529	25,464	2-40	18.2	38.9	41.4	.45	29.7	13,980	10.0	31.4	.25	16.3
9	Jul 14	521.1	32,202	9,443	2-40	18.1	37.7	39.8	.45	29.3	4,982	9.6	31.4	.24	15.5
10	Sep 12	53.5	3,197	733	2-40	13.7	37.9	40.2	.34	22.9	691	12.9	16.6	.32	21.6
11	Sep 15	44.8	2,723	852	2-40	19.0	38.2	38.4	.48	31.3	(4)	-	23.0	-	-
12	Sep 18	149.5	9,471	2,575	2-40	17.2	-	-	.43	27.2	(4)	-	-	-	-
		5,253.1	372,448	108,318	0-43	20.6	43.3	43.3	.50	29.1	(4)	8.7	35.6	.20	12.4
					GRID-CONNECTED OPERATION										
13	Nov 03	1,021.8	97,811	38,973	35-40	38.1	-	40.5	.95	39.9	2,937[5]	20.2	38.4	.51	21.1
14	Dec 16	1.0	110	-	-	-	-	-	-	-	(4)	-	-	-	-
15	Jan 09	308.5	28,145	11,104	35-40	36.0	37.0	38.8	.90	39.5	(4)	-	-	-	-
16	Jan 29	2.4	282	49	0-40	20.3	-	-	.51	17.3	(4)	-	-	-	-
17	Feb 28	39.6	3,753	1,412	11-40	35.7	-	-	.89	37.6	(4)	-	-	-	-
18	Mar 04	43.7	4,291	1,668	11-40	38.2	-	-	.95	38.9	(4)	-	-	-	-
19	Mar 09	1,271.1	123,442	48,452	11-40	38.1	-	-	.95	39.2	(4)	-	-	-	-
		2,688.0	257,834	101,658	0-40	37.7	37.0	40.5	.94	39.4	(4)	20.2	38.4	.51	21.1

(1) LHV = 34,600 kJ/m³n (929.0 Btu/scf)

(2) Capacity Factor = average load/plant capacity

(3) Start 1-8 Low-Grade Heat only. Thermal load was less than 50% of the power plant capacity at any time.

(4) Not recorded

(5) Data recorded for 145.5 hours only.

Power plant performance data to 1 May 1987 @ 12:30 hrs - as of 5 May, power plant was still operating.

SR13.10

Table 2

Fuel Cell Power Plant Test Data

Fuel Cell Power Plant AC Output			Three Phase AC Output									Stack DC Output		Percent Total Harmonic Distortion					
kW	kVAR	P.F.	V_{A-N}	V_{B-N}	V_{C-N}	V_{A-B}	V_{B-C}	V_{C-A}	I_A	I_B	I_C	V_{DC}	I_{DC}	V_A	V_B	V_C	I_A	I_B	I_C
GRID-ISOLATED OPERATION																			
36.3	12.5	.94 lag	122	122	122	212	213	212	115	104	105	182	232	6.50	7.06	6.70	8.23	7.34	5.39
22.8	11.0	.85 lag	122	122	122	212	212	212	66	71	70	189	168	7.03	7.26	6.73	11.6	8.08	3.90
0	-	-	126	126	126	216	216	216	-	-	-	212	-	7.03	7.26	6.73	11.6	8.08	3.90
GRID-CONNECTED OPERATION																			
39.1	7.5	.99 [illegible]	111	111	112	190	190	191	120	118	122	182	242	5.80	6.20	6.06	8.96	6.39	5.90
30.6	6.5	.98 lag	111	111	111	190	190	190	95	95	97	188	194	5.46	6.04	6.26	8.28	8.02	7.79
20.8	10	.91 lag	111	111	112	190	190	191	68	67	72	-	-	5.90	6.18	6.16	11.8	12.3	10.9
10.8	-	-	111	111	111	190	190	190	50	47	52	199	88	5.39	6.36	6.57	16.9	14.8	14.2
0	-	-	126	126	126	216	216	216	-	-	-	212	-	5.39	6.36	6.57	16.9	14.8	14.2

Figure 1. Site of the 40 kW PAFC Power Plant at B.C. Hydro

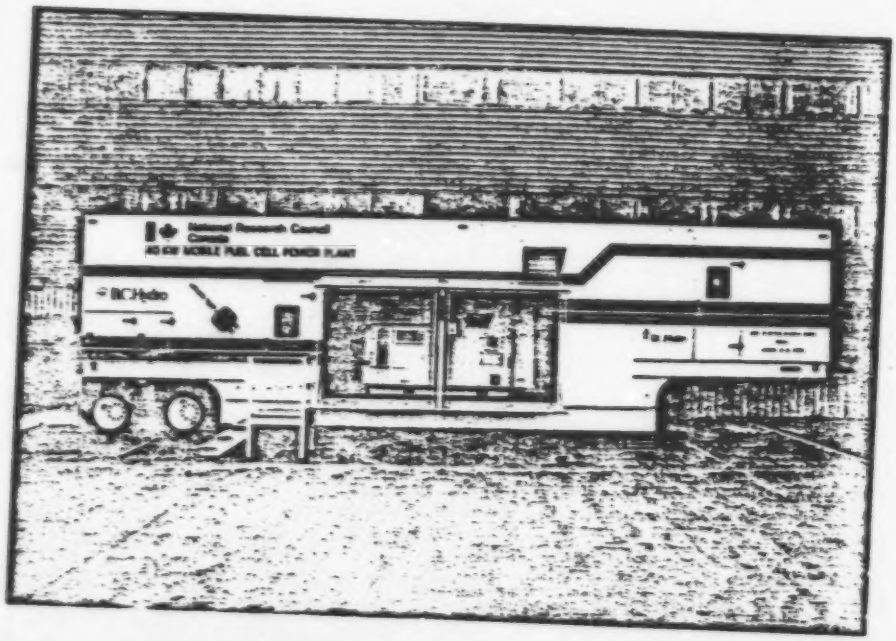

Figure 2. 40 kW Mobile Fuel Cell Power Plant at B.C. Hydro

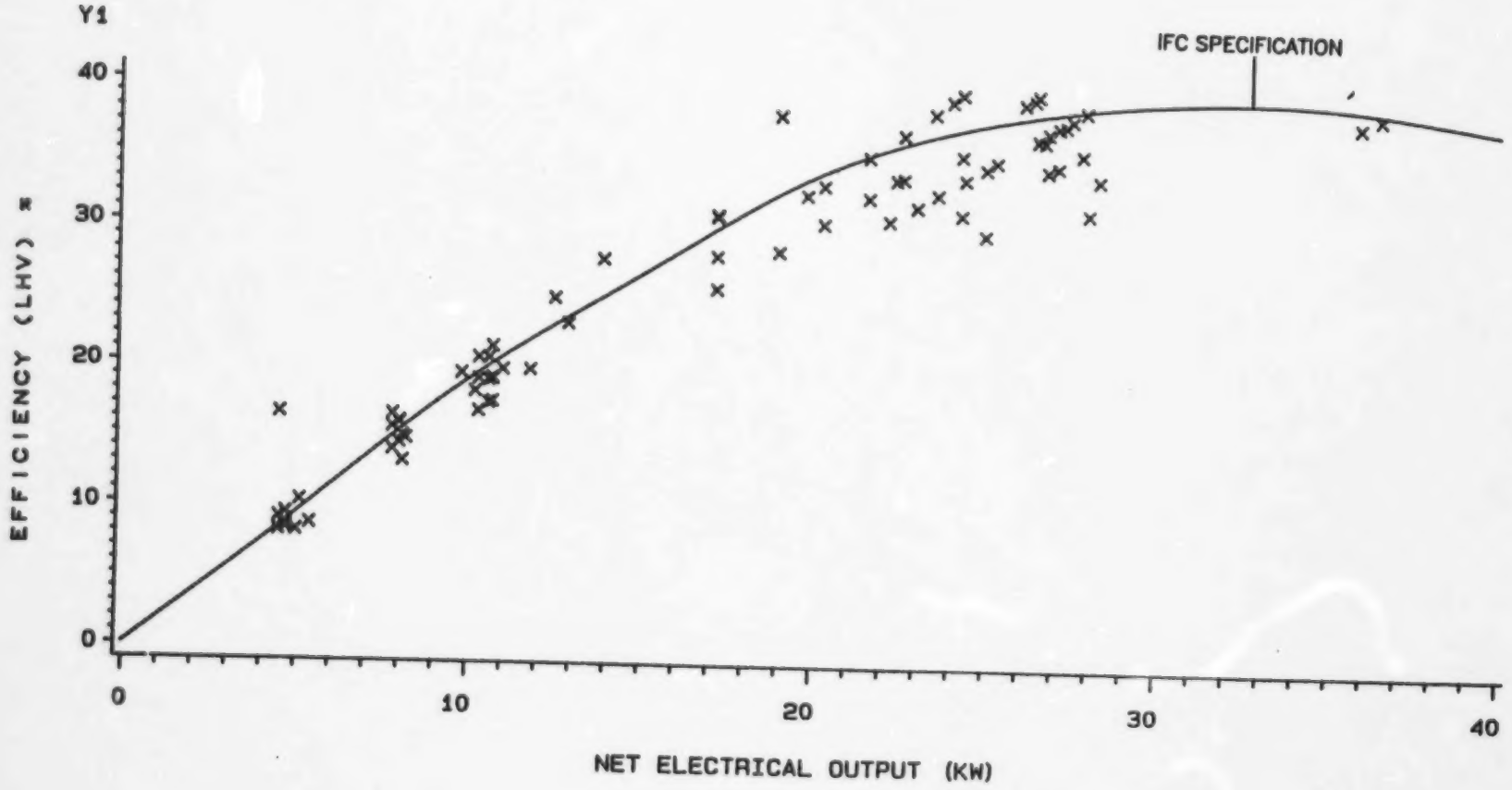

FIGURE 3. ELECTRICAL EFFICIENCY Vs. POWER LEVEL

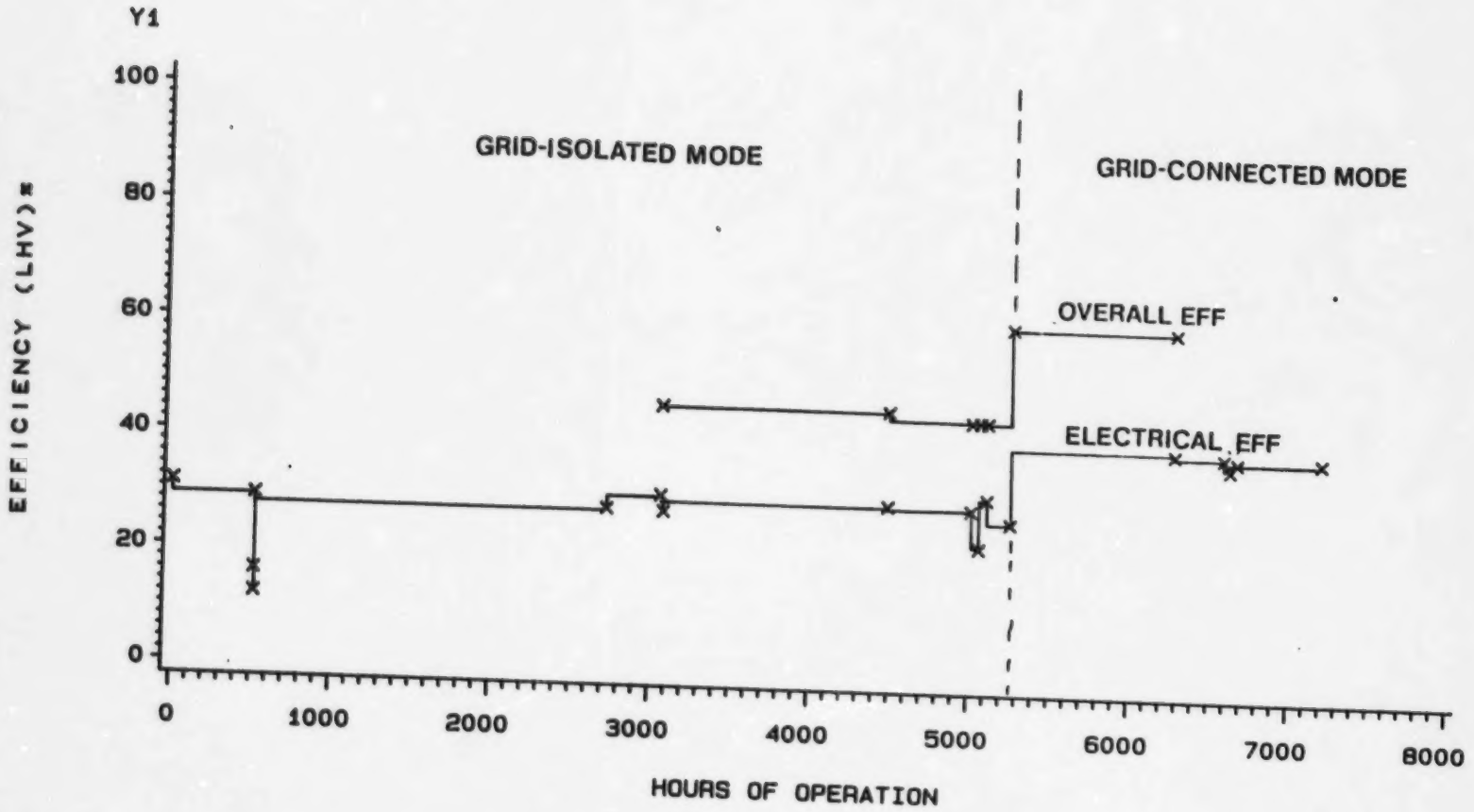

FIGURE 4. ELECTRICAL AND OVERALL EFFICIENCY VS. HOURS OF OPERATION

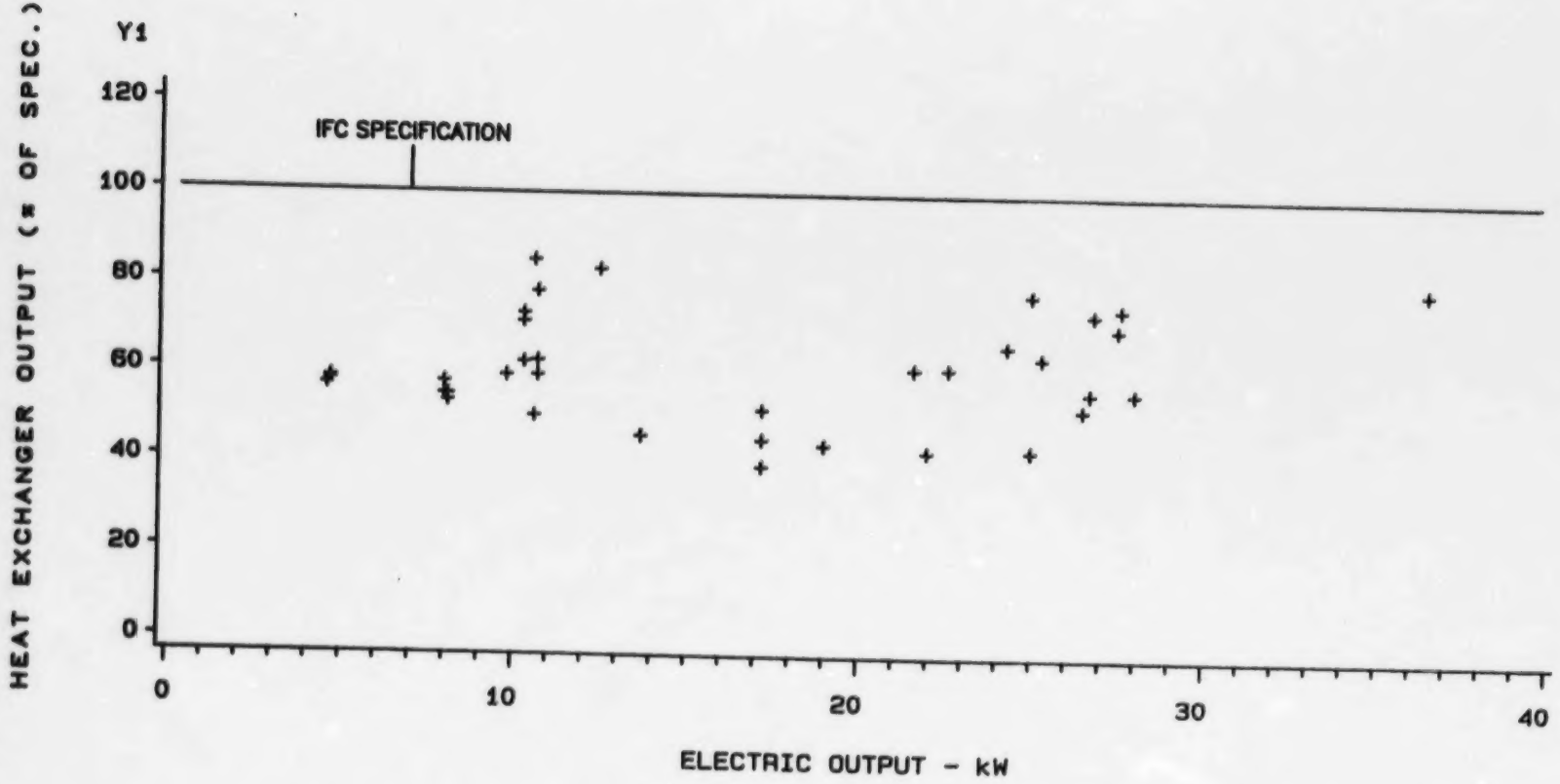

FIGURE 5. LOW-GRADE HEAT RECOVERY

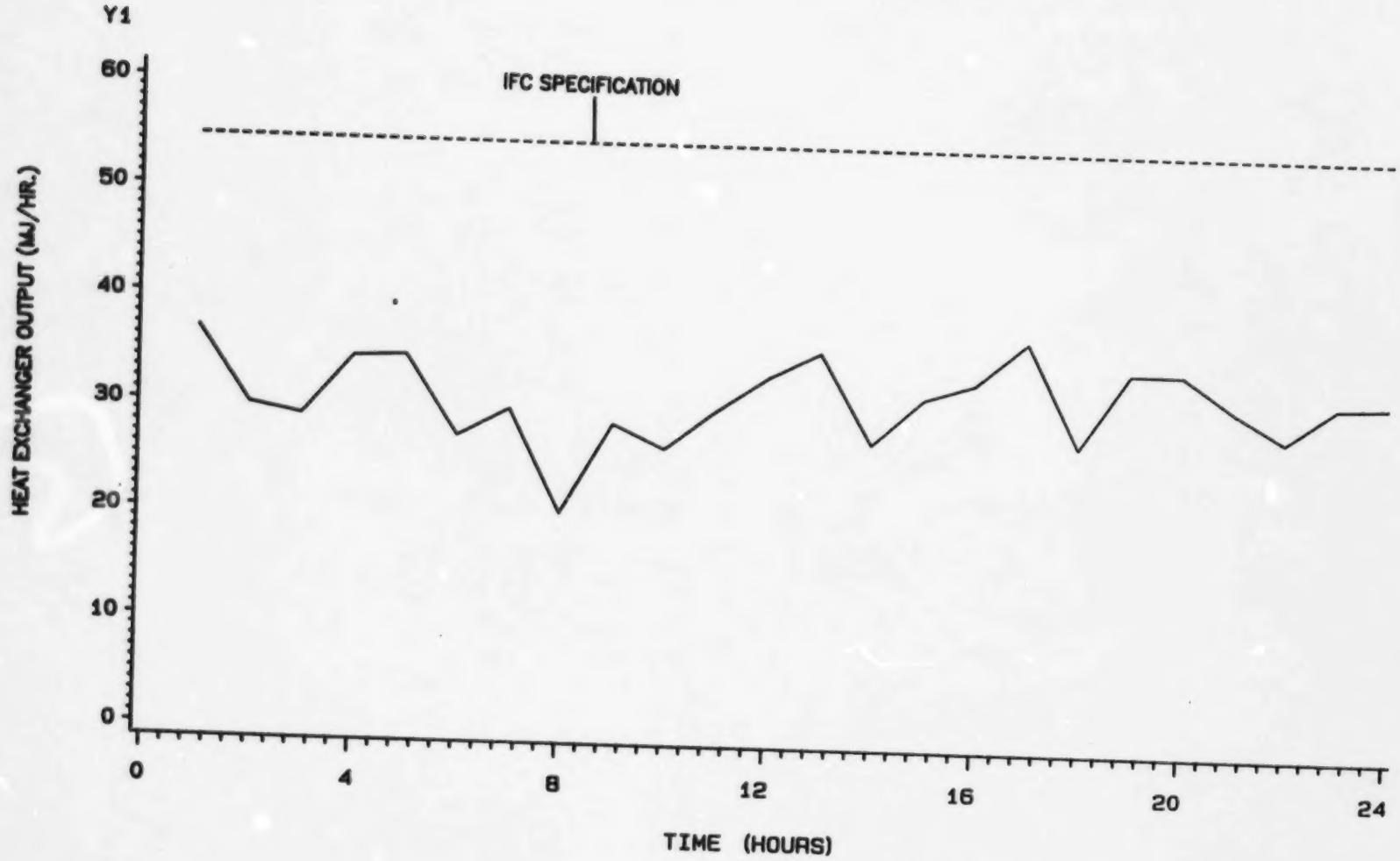

FIGURE 6. HIGH-GRADE HEAT REOVERY.

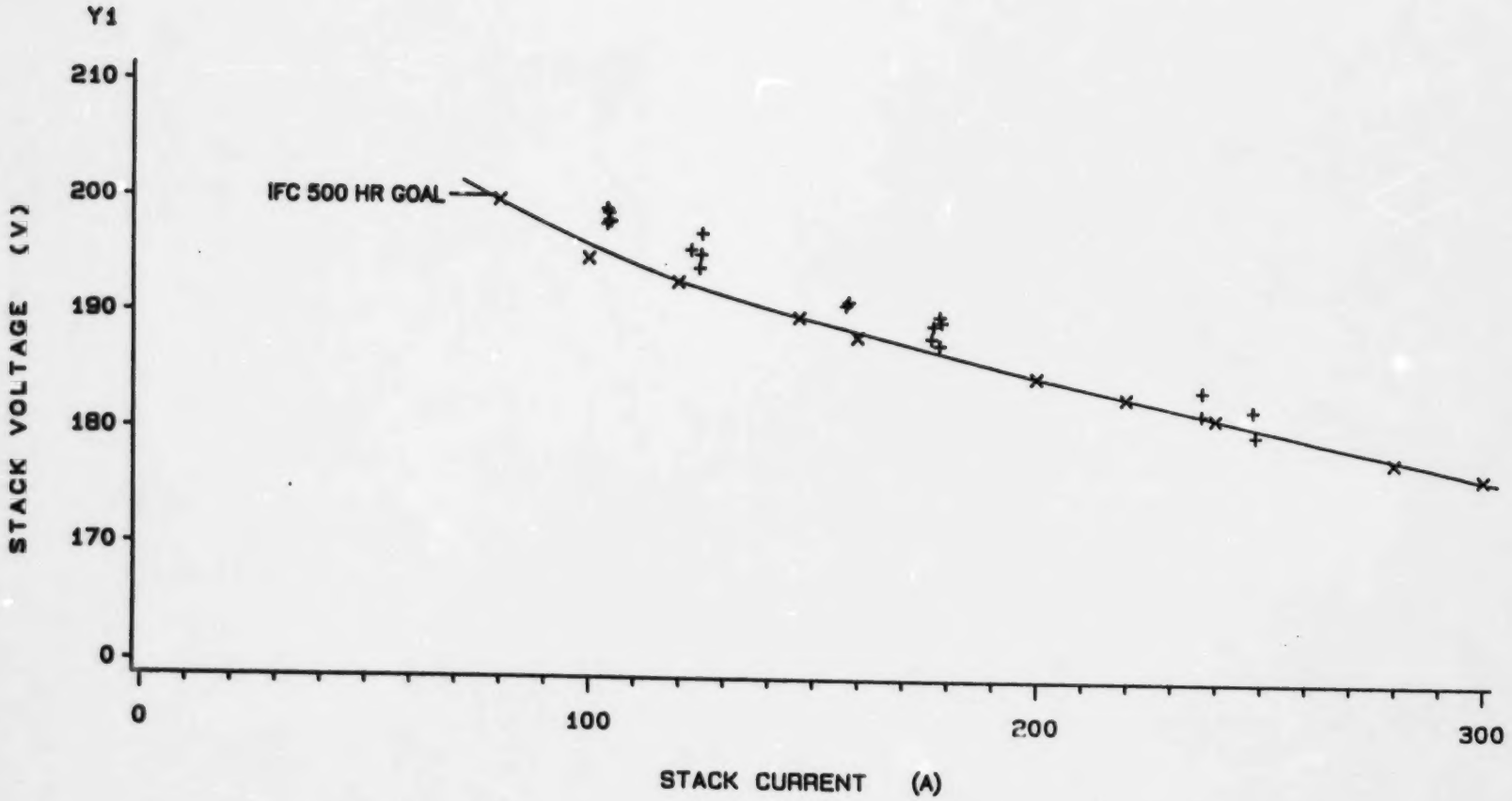

FIGURE 7. FUEL CELL STACK PERFORMANCE

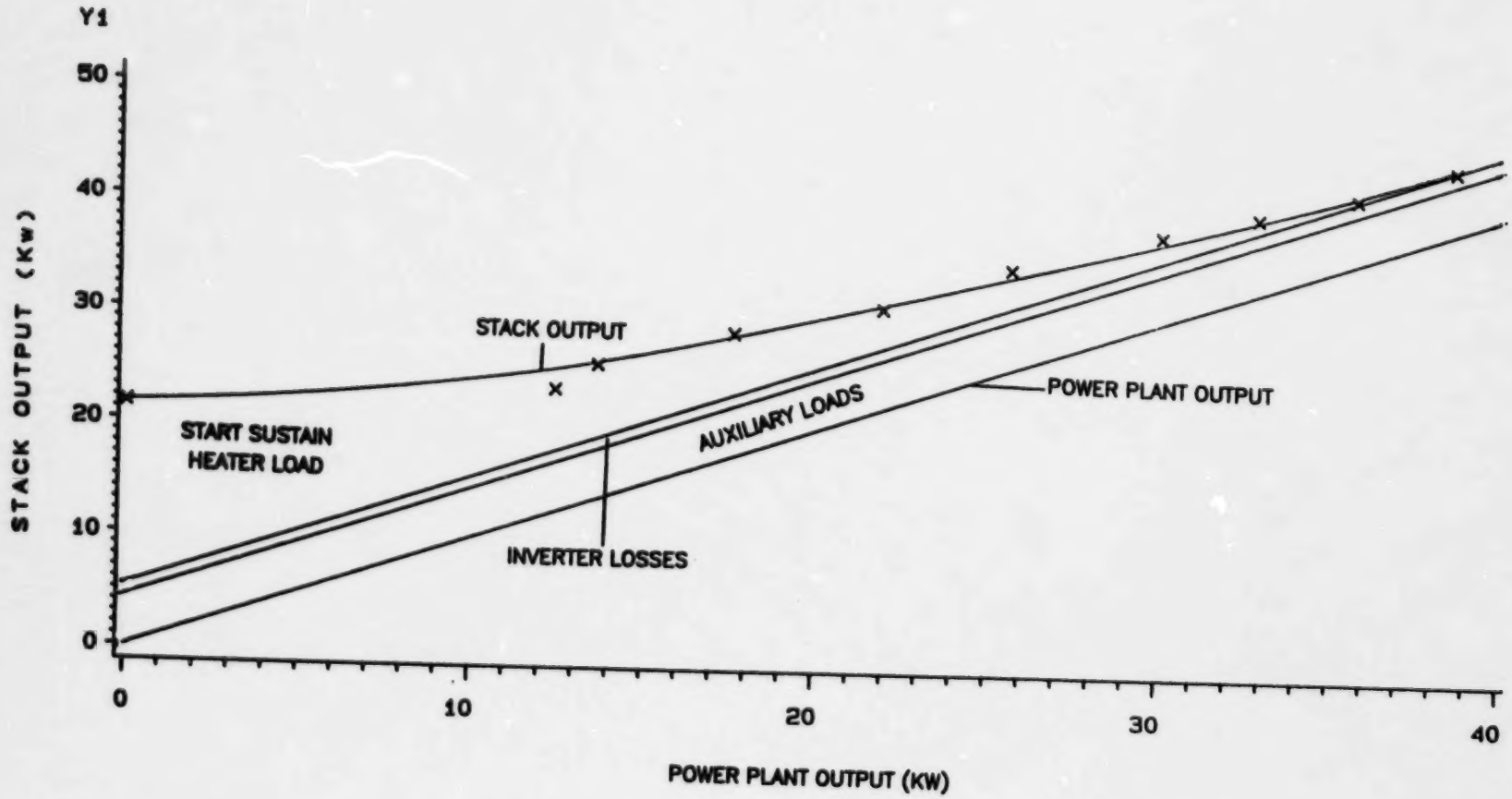

FIGURE 8. NET ELECTRICAL POWER PLANT OUTPUT Vs. FUEL CELL STACK OUTPUT

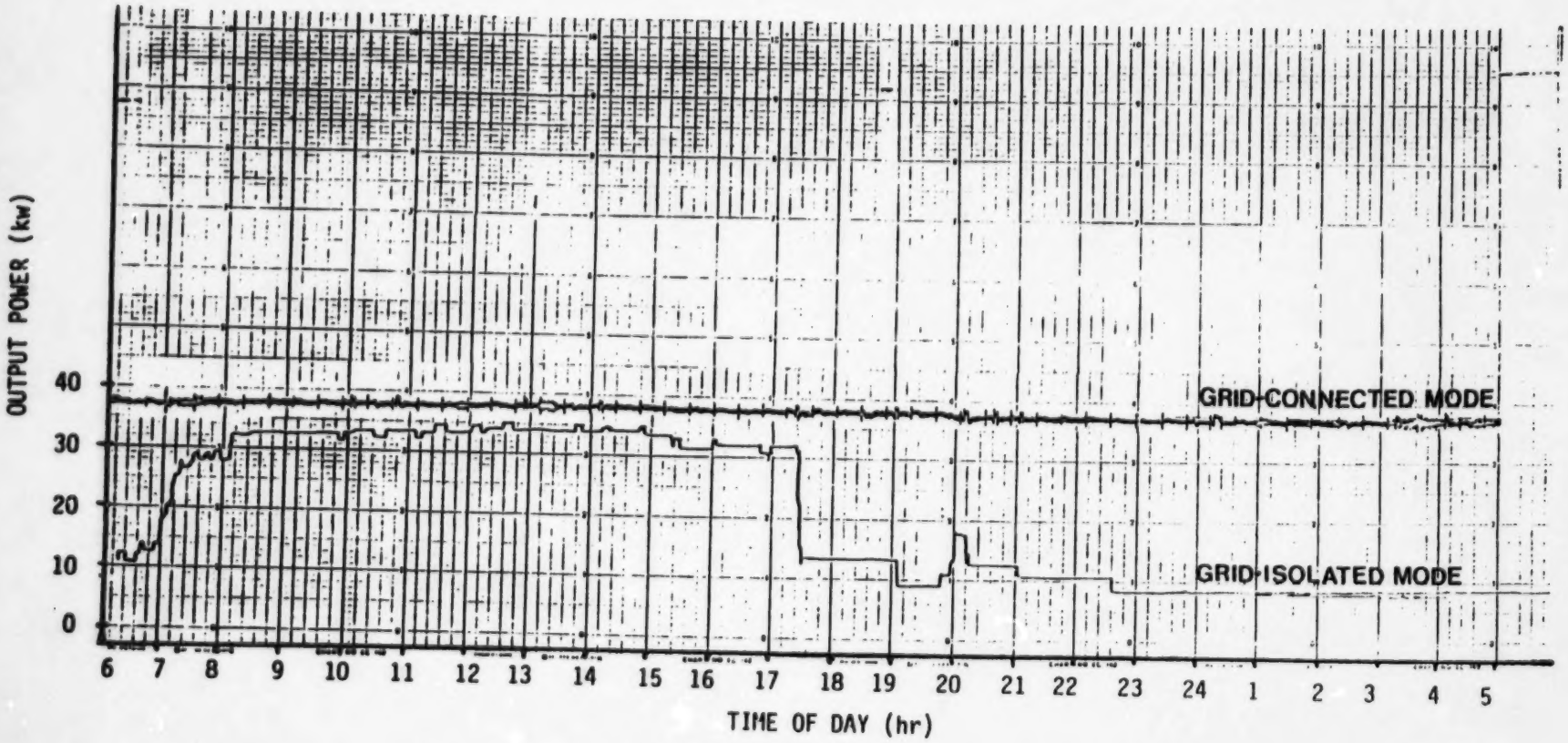
OUTPUT POWER (kw)
40
30
20
10
0
GRID-CONNECTED MODE
GRID-ISOLATED MODE
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 1 2 3 4 5
TIME OF DAY (hr)

Figure 9 - Fuel Cell Power Plant Load Following Characteristics

APPENDIX A

Commissioning and Start-up Data

(October-November 1985)

The installation of the power plant was essentially complete at the beginning of October 1985. The IFC field engineer arrived at the site on 15 October and the commissioning of the power plant began in accordance with the Operating Manual provided by IFC.

As part of the commissioning, the power plant was retrofitted to the latest standards and several modifications and repairs to the power plant were made. These included:

1. Installation of the Mechanical Retrofit Kit (Retrofit Kit A).

   This retrofit kit was supplied by IFC and included

   - modifications to the nitrogen system
   - relocation of the half stack voltage box and inverter fan
   - replacement of water pressure regulator
   - upgrading of gas valves
   - power plant freeze protection
   - upgrading of fuses and wiring for feedwater pump and cooling fan
   - installation of new cabinet heater fuses

2. Installation of the Electrical Retrofit Kit (Retrofit Kit B).

   This retrofit kit was supplied by IFC and included:

   - upgrading of printed circuit boards
   - upgrading of half stack voltage box
   - upgrading of natural gas ignition and flame safeguard system

3. Modification of the Water Treatment System.

This modification was made by B.C. Hydro and included a provision for the rejection of the water condensate from the low-grade heat exchanger and the exhaust gas condenser. Instead of recycling, these condensates were rejected and fresh demineralized make-up water added to the water deaerator as required, thus minimizing the suspended solids concentration in the cooling water and the probability of obstructing the water flow in the fuel cell stack coolant loop. In addition, two Barton differential pressure transducers (pressure gauges) were installed; one to measure the pressure drop across the calibrated flow orifice in the coolant loop, and the other to measure the pressure drop through the fuel cell stack. Arrangements have been made for the outputs from the pressure transducers to be read by the data logger.

4. Modification of the High-grade Heat Recovery System.

This modification was made by B.C. Hydro and included the installation of a low-flow by-pass (1/4 in tube) of the check valve CV400 in the high-grade heat exchange loop on the customer side. This allowed a constant low volume water flow through the high-grade heat exchanger on the customer side thus preventing dry-out.

5. Coolant Water Pump Replacement and Coolant Loop Flush.

The coolant water pump PMP301 and the cooling system pipes were excessively corroded when the unit was received. The centrifugal water pump was seized and could not be freed. Consequently, the pump was replaced. The coolant loop was thoroughly flushed with clean demineralized water to remove suspended iron oxide particulates.

6. Coolant Water Flow Problems.

The inadequate coolant water flow was one of the major problems during the commissioning of the power plant. Automatic shut-downs of the power plant were caused by the insufficient water flow in the cooling loop.

It was observed that the high-grade heat recovery in the high-grade heat exchanger and the heat rejection in the thermal control heat exchanger HEX 308 had a dramatic effect on the coolant water flow rate. The flow rate dropped below the minimum level for as long as 30 seconds when the fan operated.

It is believed that the loss of the coolant water flow was due to the severe quenching of the water in the return loop to the steam separator and the water circulation pump PMP 301 caused by the overcooling of the water in the thermal control heat exchanger HEX 308. The quenching of the water resulted in the lowering of the circulation pump inlet head pressure and consequent cavitation in the pump and low water flow which caused an automatic power plant shut-down.

7. Output Breaker B-1 Operation Problems.

The output breaker B-1 is a thermal magnetic 3 pole 240 Vac, 225 A circuit breaker with undervoltage trip for 120 V, 50/60 Hz with external connection. It is designed to open instantaneously (trip) when the inverter experiences an overload or a fault.

The operation (tripping) of the output breaker was occurring inconsistently for no apparent reason. Thus the power plant operated continuously for days at full load without the output breaker tripping, and on other occasions, the output breaker would trip at external loads of only 30 kW.

It is believed that the output breaker operated because of a perceived overload condition by the inverter. The inverter feeds two loads; the internal heaters, pumps and other power plant components and the external power plant load. Although the external load was only in the 30 kW range, the internal loads caused the inverter to see an overload condition which initiated the operation (tripping) of the output breaker. The excessive internal load was caused by the start sustain heaters being energized at power outputs for which they were not normally required and on occasion ran in conflict with the heat rejection cycles.

The operations of the output breaker B-1 did not cause a shutdown of the power plant.

8. Miscellaneous Investigations and Problem Solving.

Several leaks were found in the water treatment system and the coolant loop. These were repaired. Two check valves in the feed water systems leaked and were replaced.

The DAS readout of the fuel cell half stack voltage was incorrect. The error was corrected.

The centrifugal circulation pump rotated in reverse thus causing a reduced water flow. The lead wires to the pump were reversed which resulted in the correct rotation and the increased water flow.

The operation of the fuel gas control valve was unreliable. The valve was repaired.

The flow control characteristics of the coolant water control valve were investigated and necessary adjustments made.

9. Power Plant Start-up.

The first power plant start-up occurred on 7 November 1985. Power plant start-up was automatic following manual initiation of the start and was accomplished in approximately 5 hours. The power plant operated for 2.5 hours between 0 and 32 kW electrical load when it was automatically shut down because of the loss of cooling water flow.